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## Symmetry energy effects in the neutron star properties

D.E. Alvarez-Castillo, S. Kubis

*H.Niewodniczański Institute of Nuclear Physics, Radzikowskiego 152, 31-342  
Kraków, Poland*

### Abstract.

The functional form of the nuclear symmetry energy has only been determined in a very narrow range of densities. Uncertainties concern both the low as well as the high density behaviour of this function. In this work different shapes of the symmetry energy, consistent with the experimental data, were introduced and their consequences for the crustal properties of neutron stars are presented. The resulting models are in agreement with astrophysical observations.

### 1. introduction

The energy per particle used to described neutron star interiors can be expressed in terms of baryon number density  $n = n_p + n_n$  and isospin asymmetry  $\alpha = \frac{n_n - n_p}{n}$  of the system:

$$E(n, \alpha) = V(n) + E_s(n) \alpha^2 + O(\alpha^4) \quad (1)$$

If instead of  $\alpha$  the proton fraction  $x$  is introduced then  $\alpha = (1 - 2x)$ , which proves to be useful. In the model used here the only constituents of stellar matter are nucleons and leptons: electrons and muons. Around and above the nuclear density  $n_0 = 0.16 \text{ fm}^{-3}$  nucleons and leptons form a quantum liquid, which stands for liquid core of the neutron star. Slightly below  $n_0$  matter cannot exist as a homogeneous fluid - the one-phase system is unstable and the coexistence of two phases is required. At these densities matter clusterizes into positive nuclei immersed in a quasi-free gas of neutrons and electrons, most likely forming a Coulomb lattice with solid state properties and corresponds to the crust covering the liquid core of a star.

For typical NS masses, between  $1-2 M_\odot$ , most of the stellar matter is occupied by the core, so the global parameters like the mass, radius, moment of inertia are completely determined by the functional form of the Eq. (1). Whereas the isoscalar part  $V(n)$  corresponds mainly for the stiffness of Equation of State (EOS) which is relevant for the maximum mass of NS, the isovector part  $E_s(n)$  is responsible for the chemical composition of the matter (see (Kubis & Alvarez-Castillo 2012) for details). Both functions  $V(n)$  and  $E_s(n)$  have been implemented by means of Bézier functions composed of control points (Wikipedia 2012)

$$\mathbf{B}(t) = \sum_{i=0}^n \binom{n}{i} (1-t)^{n-i} t^i \mathbf{P}_i, \quad t \in [0, 1] \quad (2)$$

where  $\binom{n}{i}$  is the binomial coefficient and the  $n + 1$  control points  $\mathbf{P}_i$ , ( $i = 0, 1, 2 \dots n$ ) define the Bézier curve of degree  $n$ . In this way the isoscalar part  $V^{APR}$  follows the shape of the stiffest APR model (A18+UIX) (Akmal et al. 1998) up to 10 times saturation density  $n_0 = 0.16 \text{ fm}^{-3}$ . By use of a Bézier curve the model was corrected to fulfill the saturation point properties, like binding energy -16 MeV and compressibility  $K_0 = 240 \text{ MeV}$  which were not satisfied by the original A18+UIX. With it, the most massive neutron star observed of about  $2 M_\odot$  (Demorest et al. 2010) can be created within this model. For the isovector part, the symmetry energy  $E_s$ , four different models sharing the same high density behaviour but having different slopes at saturation density have been introduced. The measured values of  $E_s(n_0)$  and  $L$  (related to the slope of  $E_s$ ) of about 30 MeV and 40-120 MeV are used for drawing the  $E_s$  curves. All of them satisfy the DUrca constraint that dictates that low mass neutron stars must not cool by DUrca process (Popov et al. 2006) related to the proton fraction  $x$  inside the star, which must stay below the DUrca proton fraction threshold  $x$ . Figure 1 shows these symmetry energy forms and the resulting proton fractions together with the DUrca threshold. Control points for  $V^{APR}$  are presented in table 2 whereas for  $E_s$  can be found in (Kubis & Alvarez-Castillo 2012).

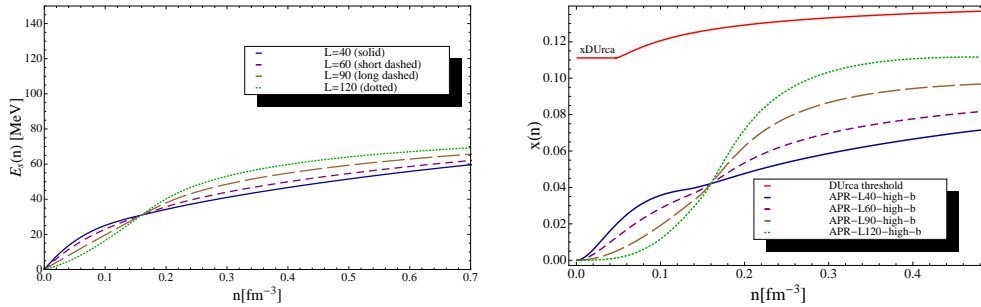


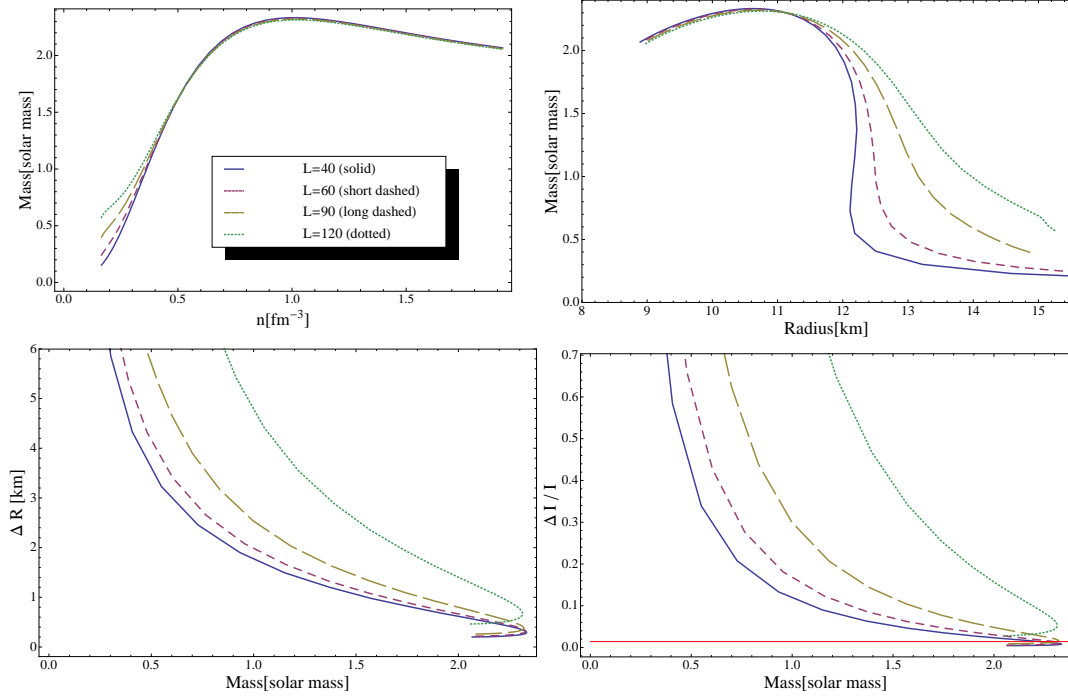
Figure 1. *Left.* Different symmetry energy shapes for the APR-L-high-b models which avoid DUrca cooling for low NS masses. *Right.* Proton fraction as a function of baryon number density for these models and DUrca threshold.

## 2. Neutron star properties

To determine the neutron star properties two EoS describing its core and its crust are joint at equal pressure and density. For the crust the SLy EOS composed of different parts whose table can be found in (Ioffe 2012) has been used. The liquid core is described by Eq. (1) and the Bézier curves described above. To determine the crust-core transition three different methods are used which are presented in (Kubis & Alvarez-Castillo 2012) and the resulting transition densities  $n_c$  are presented in table 1. The macroscopic properties like radius, mass, moment of inertia are derived in the framework of General Relativity by solving the TOV equations and the crust thickness is derived by the use of  $n_c(K_\mu)$  as described in (Alvarez-Castillo & Kubis 2011). Figure 2 shows the resulting neutron star properties for each family. They all produce high enough masses and present thick crusts. In particular the moment of inertia carried by the crust does not impose stringent constraints due to the glitch model restriction (Link et al. 1999).

Table 1. Crust-core transition densities for the *APR-L-high-b* models.

model	$n_c(Q)$	$n_c(K_\mu)$	$n_c(1 \leftrightarrow 2)$
APR-L40-high-b	0.103076	0.11012	0.116185
APR-L60-high-b	0.0922071	0.101941	0.104926
APR-L90-high-b	0.0870974	0.102523	0.103922
APR-L120-high-b	0.115633	0.142939	0.147017

Figure 2. Neutron star features for the *APR-L-high-b* models. The horizontal line in the right lower figure represents the glitch constraint from (Link et al. 1999).

It is important to mention that the inclusion of  $V^{APR}$  in these models is crucial for creating massive enough neutron stars. Furthermore the particular form of  $E_s$  fulfills the DURca requirement. These both constraints cannot be satisfied in parallel with other isoscalar parts not so stiff, like is the case of the PAL parametrization presented in (Kubis & Alvarez-Castillo 2012). Therefore the models here are good candidates for the EoS that can be compared to microscopic approaches. Lately a new study that combined different laboratory measurements points out values of  $E_s(n_0) \approx 32$  MeV,  $L \approx 50$  MeV with an error of a few MeV (Lattimer & Lim 2012). From that, one may conclude that models with low  $L$  values are preferable.

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Table 2. Bézier control points for the  $V^{APR}$  isoscalar function which follows the APR A18+UIX EoS at high  $n$ .

$\mathbf{P}_0$	$\mathbf{P}_1$	$\mathbf{P}_2$	$\mathbf{P}_3$
(0.0016, 0.4649)	(0.08, -20.9676)	(0.16, -14.6553)	(0.24, -27.2516)
$\mathbf{P}_4$	$\mathbf{P}_5$	$\mathbf{P}_6$	$\mathbf{P}_7$
(0.48, -29.7266)	(0.8, 86.6426)	(1.12, 320.0992)	(1.6, 1093.7393)

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